WWW.IJRPR.COM

International Journal of Research Publication and Reviews

Journal homepage: www.ijrpr.com ISSN 2582-7421

Anisotropic Mechanical Properties of 3D Printed Poly-Lactic Acid Parts in the Plane Stress State

Iman Zohourkari

Assistant Prof., Department of Mechanical Engineering, Birjand University of Technology, Birjand, P. O. Box: 9719866981, Iran
*DOI: **https://doi.org/10.55248/gengpi.2023.4.3.31997***

A B S T R A C T

The 3D printing process is an efficient and cost-effective production method for the rapid manufacture of parts that are complex in terms of geometry, structure and mechanical behavior. Studying the mechanical behavior of these structures is very important to understand and optimize the performance of 3D printed materials. In this article, the mechanical properties of 3D printed parts for PLA material are studied based on the constitutive stress-strain relationship in a plane stress state, and the effect of fabrication angle on the anisotropy properties of the material is analyzed using simple tensile tests in different material directions. Assuming an orthotropic behavior, the changes in strength due to anisotropy are investigated. It has been observed that the assumption of orthotropic behavior is a suitable assumption to express the mechanical behavior of fabricated materials using 3D printing methods. The results obtained can be used in software for numerical analysis of 3D printed parts similar to composite modeling.

Keywords: Anisotropy, Fused deposition modelling, Raster angle, Additive manufacturing, stiffness

1. Introduction

Today, the face of FDM has changed from rapid prototyping to a fast and efficient manufacturing strategy [1-4]. Therefore, this development underscores the need for a thorough investigation of the mechanical properties and behavior of parts manufactured by FDM. However, understanding the mechanical behavior is complex as it involves many parameters that must be considered when designing and optimizing the process to achieve the desired goal. It has been reported that 3D printed parts made by FDM can be considered as a laminated composite material [5]. So, it offers good potential to study and improve the strategies to produce applicable products with acceptable properties. Ahnet al. [5] performed several experiments to determine the effects of air gap, bead width, and screen angle on tensile and compressive strength. They find that grid orientation has an important impact on mechanical properties such as strength. In another study, Anitha et al. [6] investigated the influence of the layer thickness and showed that the performance increases as the thickness decreases. Sood et al. [7] analyzed the functional relationship between sample strength and several factors, e.g.,build orientation, layer thickness, screen angle and air gap. They reported that the strength of the samples produced by FDM is greater in the axial direction than in the transverse direction.This result shows a good resemblance to a unidirectional fiber sheet, where the strength in the fiber direction is higher than that perpendicular to it. The aim of this work is to obtain the mechanical behavior of FDM parts through limited stress-strain tests and to relate the results to constitutive relationships that exist for orthotropic composites. For this purpose, values of elastic modulus in longitudinal, transverse and other loading directions were measured with respect to the screen angle and used to study their similarity to orthotropic materials. The results obtained will be useful for the numerical simulation of 3D printed parts.

* *Corresponding author.* Tel.: +98-912-0234677; fax: +98-56-32391000.
E-mail address: Zohourkari@birjandut.ac.ir

2. Problem statement, innovations and goals

The development of additive manufacturing applications in the manufacture of end products makes it very important to develop and apply techniques to model the mechanical behavior of 3D printed parts. Anisotropic mechanical properties of manufactured parts add further complications to the design cycle. In addition, previous studies in the field of simulation mainly focus on micromechanical approaches. By determining mechanical properties related to the process parameters, it will be beneficial to perform numerical simulations and will also be applicable for the improvement and optimization of the adaptation of the 3D printing strategies. The aim of this work is therefore to obtain the mechanical behavior of FDM parts through limited stress-strain tests and to relate the results to constitutive relationships that exist for orthotropic composites.

3. Methodology

To measure and study the mechanical properties of 3D printed materials, the stress-strain relationship for orthotropic materials in the plane stress state was used to calculate the material constants such as Young's modulus and Poisson's ratios in principal directions and their changes in the global coordinate system.
Assuming the raster angle in 3D printed parts results in a similar mechanical response with fiber direction in continuous fibrous composites principal and global directions will be determined as shown in Fig. 1.

Where 1 and 2 denote raster direction and the transverse direction perpendicular to the raster respectively. X and Y denote global coordinate directions.

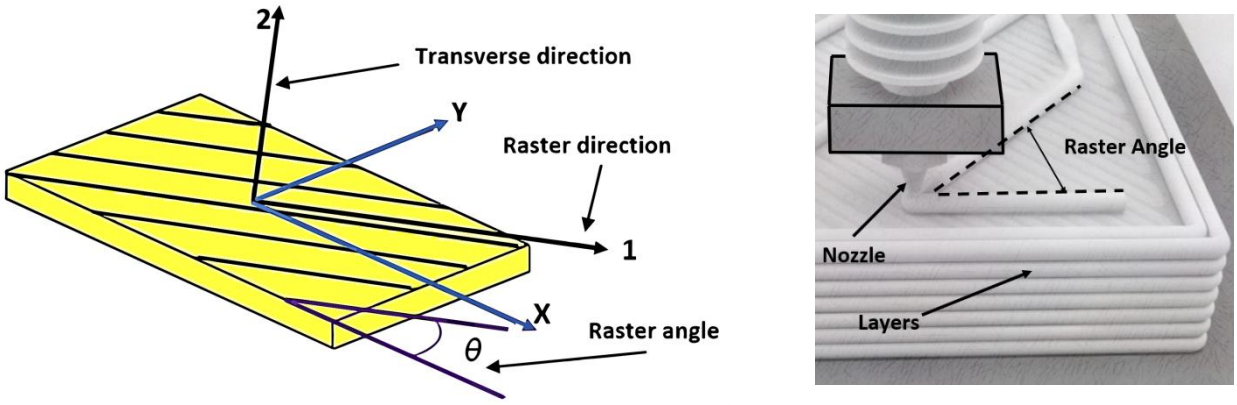

Fig. 1 - (a) material and global coordinate system; (b) 3D printing direction (Raster angle).

The Constitutive equations for orthotropic 3D printed materials in plane stress state based on principal directions can be written as Eq. (1).

$$\begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{Bmatrix} = \begin{bmatrix} Q_{11} & Q_{12} & 0 \\ Q_{12} & Q_{22} & 0 \\ 0 & 0 & Q_{66} \end{bmatrix} \begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \gamma_{12} \end{Bmatrix} \quad (1)$$

Where [Q] is the reduced stiffness matrix and its elements are defined based on mechanical constants.

$$[\bar{Q}] = \begin{bmatrix} \bar{Q}_{11} & \bar{Q}_{12} & \bar{Q}_{16} \\ \bar{Q}_{12} & \bar{Q}_{22} & \bar{Q}_{26} \\ \bar{Q}_{16} & \bar{Q}_{26} & \bar{Q}_{66} \end{bmatrix} \quad (2)$$

Rewriting the reduced off-axis stiffness matrix based on engineering constants in the global coordinate system, elastic modulus as a function of raster angle can be obtained.

$$E_x = \frac{E_1}{m^4 + \left(\frac{E_1}{G_{12}} - 2\nu_{12}\right) n^2 m^2 + \frac{E_1}{E_2} n^4} \quad (3)$$

Where $m=cos(\theta)$ and $n=sin(\theta)$

Assuming v_{12}=0.33 for PLA and applying tensile test results in raster angles other than 0° and 90°, G_{12} can be calculated by solving Eq. (3).
After the determination of the four mechanical constants in the material coordinate system, variation of elastic modulus, shear modulus, and Poisson's ratio with respect to raster angle in the global coordinate system can be obtained similarly to Eq. (3).
For the calculation of four engineering constants, test samples were prepared based on the ASTM D638-14 standard test for the tensile test of plastics. Type IV specimen was selected for tests as shown in Fig .2.

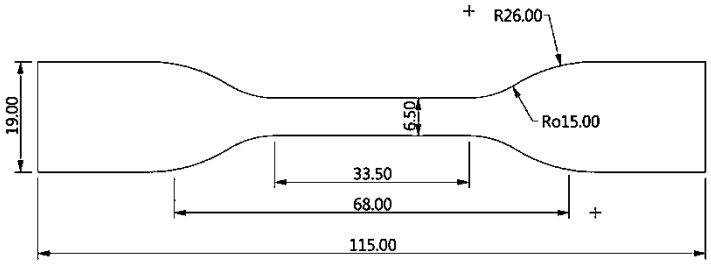

Fig. 2 - ASTM D638 Type IV specimen.

GEEETECH Prusa i3 FDM printer has been used for printing the test specimens using 1.75 mm PLA filament (Fig. 3). The printing parameters are summarized in Table 1. The printing parameters are summarized in Table 1. As shown in Fig. 4, six specimens with raster angles of 0°, 15°, 30°, 45°, 60°, and 90°, with infill density of 100% were printed and used for tensile tests. The thickness was chosen equal to 0.5 mm to guarantee the plain stress state. The printed specimens have been shown in Fig. 4.

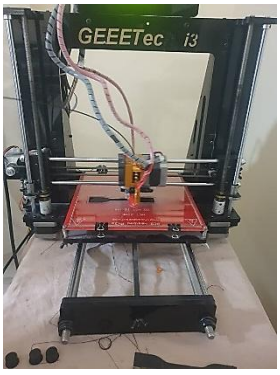

Fig. 3 - The process of 3D printing for preparation of the test samples.

Fig. 4 - FDM printed specimens with various raster angles.

Table 1: The printing parameters applied to the test specimens.

Filament	Nozzle size	Nozzle Temp.	Heatbed Temp.	Layer height	Print speed
PLA 1.75 mm	0.3 mm	200°C	60°C	0.25 mm	60 mm/s

To obtain stress-strain relations and orthotropic mechanical properties of the PLA samples, tensile tests have been done using Santam STM-250 universal test machine based on ASTM D638-14. (Fig. 5)

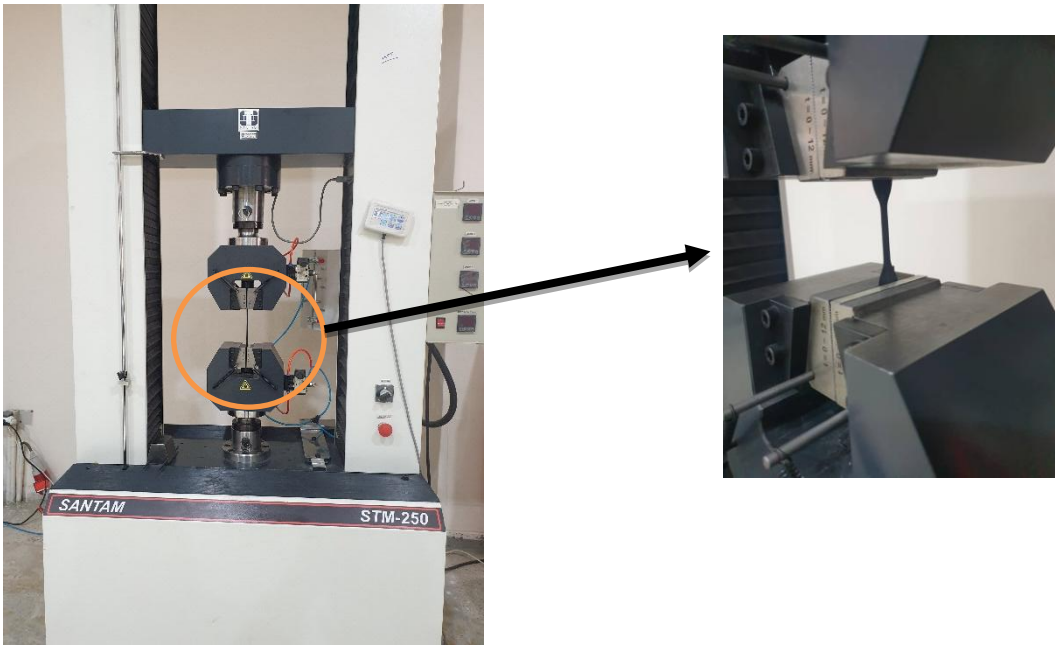

Fig. 5: tensile test apparatus.

4. Results and Discussion

Stress-strain curves for the six test specimens are shown in Fig. 6.

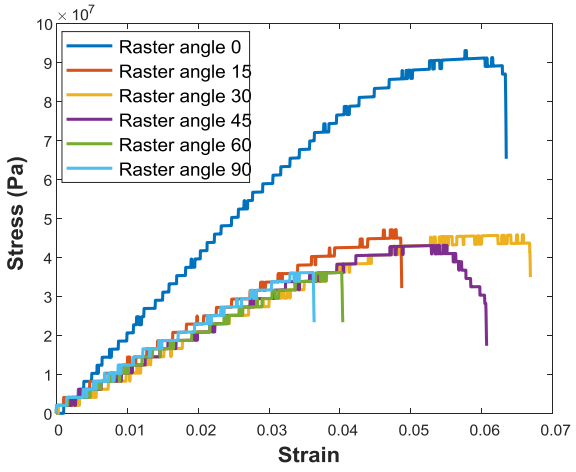

Fig. 6 - Stress-strain curves for test specimens in different raster angles.

It can be seen that the specimen with a raster angle equal to 0° shows the highest elastic module while in other angles a high decrease in the elastic module has occurred. Moreover, the specimen with 0° raster angle has the highest ultimate tensile strength and toughness.

Elastic modulus in the loading direction (X direction) has been calculated based on the slope of the curve in the elastic region. Elastic modulus in X direction for each sample, with respect to change in raster angles, were obtained from tensile tests and illustrated in Table 2.

Table 2: Elastic moduli for 3D printed test specimens in various raster angles

Sample No.	Raster angle	Elastic modulus (GPa)

1	0	1.269 (E1)
2	15	1.054
3	30	1.056
4	45	0.981
5	60	0.995
6	90	1.156 (E2)

To calculate the shear modulus in the 1-2 plane, known principal engineering constants of specimens with 15, 30, 45, or 60 raster angles can be substituted in Eq. (3). In this study, engineering constants for specimens with 30 raster angle has been chosen for calculation of principal shear modulus in 1-2 plane. So, the shear modulus was found to be 342.68 MPa.
Variation of elastic modulus due to change in raster angle has been depicted in Fig 7.

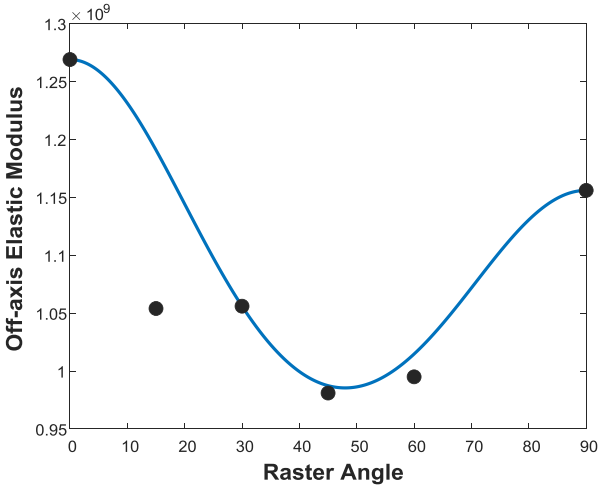

Fig. 7 - Variation of elastic modulus due to change in printing raster angle (black dots are experimental data).

It can be seen that the trend for variation of the elastic modulus obtained from the relation for orthotropic materials and the experimental data is very similar. It assures that the printed materials follow the orthotropic behavior.

5. Conclusions

- The assumption of an orthotropic behavior is a suitable postulation to predict the mechanical properties of FDM parts.
- The sample with a raster angle of 0° shows the highest elastic modulus, while at other angles a large decrease in elastic modulus has occurred.
- The minimum modulus of elasticity occurs at a raster angle of 45°.
- Shear stresses are developed while the parts are loaded in a direction other than the grid or its normal direction.This phenomenon can overcome the diffusion strength between rasters.
- The calculation of orthotropic material constants allows providing a suitable material model for numerical simulations of 3D printed parts.

Acknowledgements

The author would like to thank Mr. Mohammad Lakhi, Laboratory Manager at Central Laboratory of Birjand University of Technology, for his kind assistance in conducting the experiments.

6. References

[1] Mohammed, A. A., Algahtani, M. S., Ahmad, M. Z., Ahmad, J., and Kotta, S., 2021. "3D Printing in medicine: Technology overview and drug delivery applications". Annals of 3D Printed Medicine, 4, 100037.

[2] Park, S., Shou, W., Makatura, L., Matusik, W., & Fu, K. K., 2022. "3D printing of polymer composites: Materials, processes, and applications". Matter, 5(1), pp. 43-76.

[3] Thompson, M. S., 2022. "Current status and future roles of additives in 3D printing—A perspective". Journal of Vinyl and Additive Technology.

[4] Raheem, A. A., Hameed, P., Whenish, R., Elsen, R. S., Jaiswal, A. K., Prashanth, K. G., and Manivasagam, G., 2021. "A Review on Development of Bio-Inspired Implants Using 3D Printing". Biomimetics, 6(4), pp. 65.

[5] Ahn, S.H., Montero, M., Odell, D., Roundy, S. and Wright, P.K., 2002. "Anisotropic material properties of fused deposition modeling ABS". Rapid prototyping journal, 8(4), pp. 248-257.

[6] Anitha, R., Arunachalam, S. and Radhakrishnan, P., 2001. "Critical parameters influencing the quality of prototypes in fused deposition modelling". Journal of Materials Processing Technology, 118(1-3), pp.385-388.

[7] Sood, A.K., Ohdar, R.K. and Mahapatra, S.S., 2010. "Parametric appraisal of mechanical property of fused deposition modelling processed parts". Materials & Design, 31(1), pp.287-295.